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Review

Public health co-benefits of greenhouse gas emissions reduction: A systematic review

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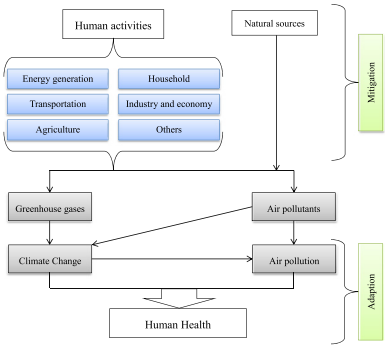
HIGHLIGHTS

- Public health co-benefits of GHG mitigation was primarily observed in five economic sectors.
- Comprehensive GHG mitigation measures across various sectors tend to provide greater ancillary health gains.
- Health co-benefits assessments of GHG reductions are based almost entirely on descriptive or modeling studies.
- Overestimation or underestimates may arise during the health co-benefits assessment of GHG mitigation strategies.
- Voluntary engagements in the use of standard methods to estimate the co-benefits of GHG abatement are needed.

GRAPHICAL ABSTRACT

Potential pathways that greenhouse gas mitigation measures result in public health co-benefits.



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ABSTRACT

Background and objectives: Public health co-benefits from curbing climate change can make greenhouse gas (GHG) mitigation strategies more attractive and increase their implementation. The purpose of this systematic review is to summarize the evidence of these health co-benefits to improve our understanding of the mitigation measures involved, potential mechanisms, and relevant uncertainties.
Methods: A comprehensive search for peer-reviewed studies published in English was conducted using the primary electronic databases. Reference lists from these articles were reviewed and manual searches were

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Climate change
Greenhouse gas emissions
Health co-benefits
Mitigation
Uncertainty

performed to supplement relevant studies. The identified records were screened based on inclusion criteria. We extracted data from the final retrieved papers using a pre-designed data extraction form and a quality assessment was conducted. The studies were heterogeneities, so meta-analysis was not possible and instead evidence was synthesized using narrative summaries.

Results: Thirty-six studies were identified. We identified GHG mitigation strategies in five domains – energy generation, transportation, food and agriculture, households, and industry and economy – which usually, although not always, bring co-benefits for public health. These health gains are likely to be multiplied by comprehensive measures that include more than one sectors.

Conclusions: GHG mitigation strategies can bring about substantial and possibly cost-effective public health co-benefits. These findings are highly relevant to policy makers and other stakeholders since they point to the compounding value of taking concerted action against climate change and air pollution.

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1. Introduction

There is robust evidence that climate change is well underway and that anthropogenic greenhouse gas (GHG) emissions, primarily from the burning of fossil fuels, are the main drivers (Solomon, 2007; Stocker et al., 2013). According to the Intergovernmental Panel on Climate Change (IPCC), the average global surface temperature rose by about 0.85 °C from 1880 to 2012, and high-end emissions projection scenarios have shown that if no further mitigation actions are taken, the globe will warm by 2.6–4.8 by the end of the century (Stocker et al., 2013; Watts et al., 2015). Even if carbon dioxide (CO_2) emissions abruptly ceased, climate change would continue for hundreds of years due to the inertia in the global climate system (Matthews and Caldeira, 2008; Solomon et al., 2009).

There are clear signs that climate change already threatens human health, directly and indirectly, and is expected to cause increasingly adverse impacts in the future (Ebi et al., 2017; Field et al., 2014; Forzieri et al., 2017; Gasparrini et al., 2017; Pachauri et al., 2014a; Smith et al., 2014; Woodward et al., 2014). Climate change can affect public health by various pathways (Fig. 1) (Field et al., 2014; McMichael et al., 2006; Seal and Vasudevan, 2011; Shannon et al., 2007). It is estimated that there were 125 million additional vulnerable adults exposed to heatwaves between 2000 and 2016, due to the increasing exposure to more frequent and intense heatwaves (Watts et al., 2017a; Watts et al., 2017b). Increasing ambient temperatures during this peroid have reduced 5.3% outdoor manual labour productivity worldwide (Watts et al., 2017b). In 2016, the value of economic losses resulting from climate-related events were reach totally US$129 billion (Watts et al., 2017a). According to the report from World Health Organization (WHO), considering only the well understood impacts of climate change, and assuming continued progress in economic development and public health protection, that climate warming is still likely to cause about 250,000 additional deaths annually worldwide between 2030 and 2050 (Hales et al., 2014). Climate change has been described as the biggest global threat confronting public health in the 21st century (Costello et al., 2009; Watts et al., 2015).

In light of the broad evidence that climate change is occurring with potentially expensive and far-reaching health consequences, urgent and substantial actions are needed, to limit disruption of the global climate. We have the means to mitigate climate change (Cheng and Berry, 2013; Pachauri et al., 2014a; Smith et al., 2014; Watts, 2009; Xia et al., 2015), but many countries are reluctant to make decisive changes (Edenhofer et al., 2014; Haines, 2012). In general, the focus lies on developing economies, reducing poverty, and improving living standards, and climate change is often perceived as a distant threat and a lower priority on the political agenda (Aunan et al., 2004; Li and Crawford-Brown, 2011). Additionally, developing countries often insist that the "common but shared responsibility" principle of the 1992 United Nations Framework Convention on Climate Change (UNFCCC) should be applied, meaning they should not have the same GHG emissions reduction obligations as developed countries until a certain level of development is achieved

(Baer et al., 2008; Costa et al., 2011). Low- and middle-income countries point out that they are only retracing the same development path taken in the past by present-day high-income countries. This highlights the worldwide challenge to find equitable low-carbon routes to achieve better health and prosperity.

Studies published in *The Lancet* have shown that appropriate climate change mitigation strategies can have additional, independent, and largely beneficial effects on public health (Haines, 2012; Watts, 2009). For instance, GHG mitigation actions aimed at reducing fossil-fuel combustion can produce health benefits by decreasing local air pollution because, GHGs and air pollutants are, to a large extent, emitted from the same sources (Fig. 2) (Aunan et al., 2006; Chae and Park, 2011; Cifuentes et al., 2001b; Watts et al., 2017b). Win-win opportunities of this kind may make GHG mitigation strategies more attractive and encourage their implementation (Edenhofer et al., 2014; Field et al., 2014; Shindell et al., 2012; Watts et al., 2017b). At the very least, co-benefits can reduce or exceed the costs of taking actions against climate change and therefore, can strengthen the case for climate change mitigation policies in the face of scientific uncertainty (Kelly et al., 2017; Nemet et al., 2010).

Although the scientific literature has focused on the "health co-benefits" of GHG mitigation in recent years, to date, no comprehensive review has been conducted specifically assessing the relationship between GHG emissions reduction and ancillary health benefits. Summarizing and understanding these co-benefits on health can provide helpful information for policy makers in their decision-making processes to prioritize the development and implementation of win-win GHG mitigation measures that can help protect people from the impacts of climate change (Cheng and Berry, 2013; Pachauri et al., 2014a; Watts et al., 2015). Accordingly, the purpose of this review is to synthesize the current evidence of public health co-benefits of GHG emissions reduction in different economic sectors. We aim to summarize what is presently known about the pathways by which GHG reductions can bring ancillary health benefits and the relevant uncertainties associated with process of the health co-benefits assessment.

2. Methods

2.1. Relevant definitions

According to the Fifth Assessment Report of the IPCC, the term "co-benefits," also known as ancillary benefits, refers to the positive effects that a policy or measure aimed at a particular objective has on other objectives, irrespective of the net effects on overall social welfare (Pachauri et al., 2014a; Smith et al., 2014). We define public health co-benefits as measures to reduce the emissions of climate-warming pollutants (mainly GHGs), which also hold the potential

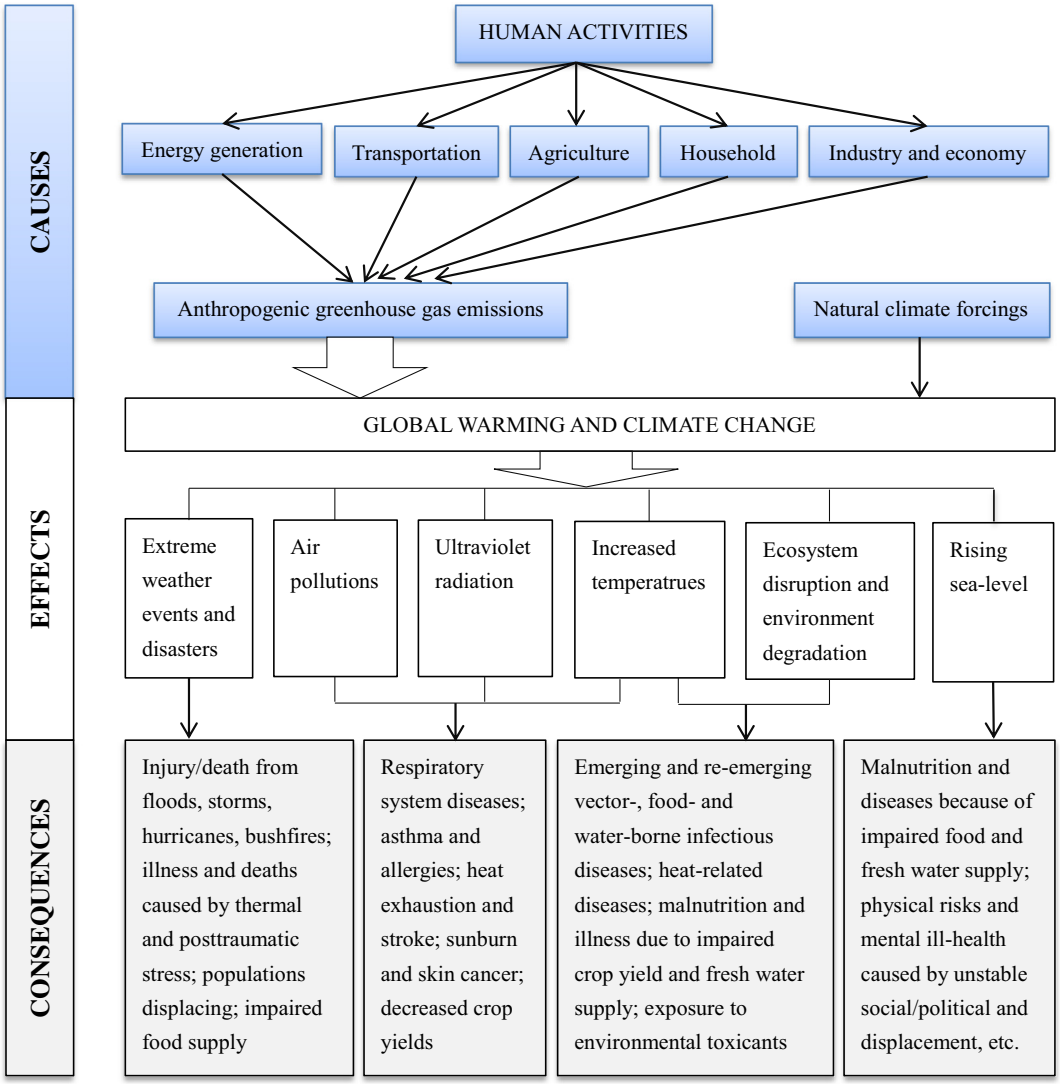
CAUSES
EFFECTS
CONSEQUENCES
HUMAN ACTIVITIES
Energy generation
Transportation
Agriculture
Household
Industry and economy
Anthropogenic greenhouse gas emissions
Natural climate forcings
GLOBAL WARMING AND CLIMATE CHANGE
Extreme weather events and disasters
Air pollutions
Ultraviolet radiation
Increased temperatrues
Ecosystem disruption and environment degradation
Rising sea-level
Injury/death from floods, storms, hurricanes, bushfires; illness and deaths caused by thermal and posttraumatic stress; populations displacing; impaired food supply
Respiratory system diseases; asthma and allergies; heat exhaustion and stroke; sunburn and skin cancer; decreased crop yields
Emerging and re-emerging vector-, food- and water-borne infectious diseases; heat-related diseases; malnutrition and illness due to impaired crop yield and fresh water supply; exposure to environmental toxicants
Malnutrition and diseases because of impaired food and fresh water supply; physical risks and mental ill-health caused by unstable social/political and displacement, etc.

Fig. 1. Schematic summary of climate change determinants and potential pathways through which climate change affects human health.

to improve human health, independent of the effects on climate change.

GHGs, defined under the Kyoto protocol, include CO_2, methane (CH_4), nitrous oxide (N_2O), and three halocarbons, and the effects of GHG mixtures are commonly reported in terms of CO_2 equivalents (CO_2-eqs) (Breidenich et al., 1998). In order to limit mean global warming to 2 °C, it is necessary to reduce the emissions of not only the official GHGs but all climate-active pollutants with high positive radiative forcing (RF). These include, black carbon (BC) and O_3 (Kopp and Mauzerall, 2010; Shindell et al., 2012; Smith et al., 2009). Thus, in the present study, we include O_3 and BC as CO_2-eqs (greenhouse pollutants).

2.2. Data sources and search strategy

A comprehensive literature search for peer-reviewed studies published up to March 2015 was conducted using the electronic databases PubMed, Embase, Web of Science and ScienceDirect (Elsevier). We subscribed to the email alert service of each selected database so that we could receive (follow-up) uptodate information on related studies. In addition, relevant websites and materials from the WHO, the IPCC, the International Energy Agency (IEA), Global Change (http://www.globalchange.gov/), and the World Bank were also searched for further information. References in the retrieved articles were examined and then manual searches were conducted to recover relevant papers that were not included in the major databases. Only English-language articles were included in the initial search.

Our primary search used the following Medical Subject Headings (MeSH terms) from the US National Library of Medicine and key words: "greenhouse gas," "GHG," "carbon," "CO_2," "black carbon," "methane," "ozone," "capture," "cut," "low," "limit," "mitigation," "reduce," "sequestration," "benefit," "co-benefit," "effect," "impact," "cost," "disease burden," and "health." The search terms were adapted to the different databases in order to facilitate a comprehensive search, and the general search strategy is presented in Table 1.

2.3. Inclusion criteria

Our inclusion criteria were based on the primary searches related to GHG emissions reduction and public health co-benefits.

- Types of studies: only original, peer-reviewed journal articles were included. Reviews, reports, conference abstracts, books, and meta-analyses were excluded.
- Research factors: GHG emissions reduction was one of the exposure indicators of interest.
- Target outcomes: at least one public health co-benefit indicator was analyzed.
- Effect measures: the quantitative association of GHG abatement with ancillary health gains was estimated.

2.4. Study selection

Three of the present authors (JHG, JL, and SHG) independently screened the results of the literature search for the potential relevance, based on the information presented in article titles and abstracts. The full text of each article identified as potentially relevant by either one or more review authors was retrieved. The same three authors independently assessed the eligibility of full text articles according to inclusion criteria. When the eligibility assessment varied among review authors, a discussion was held to reach consensus.

2.5. Data extraction

Two authors (JHG and JL) extracted data independently from the final selected references using a pre-designed data extraction form. Studies that met the eligibility criteria were retrieved and the following key information was obtained: publication date, study region, sectors involved, mitigation measures, climate benefits, and health co-benefits. The data were then cross-checked and any discrepancies or disagreements were discussed by the data extractors and resolved through consensus.

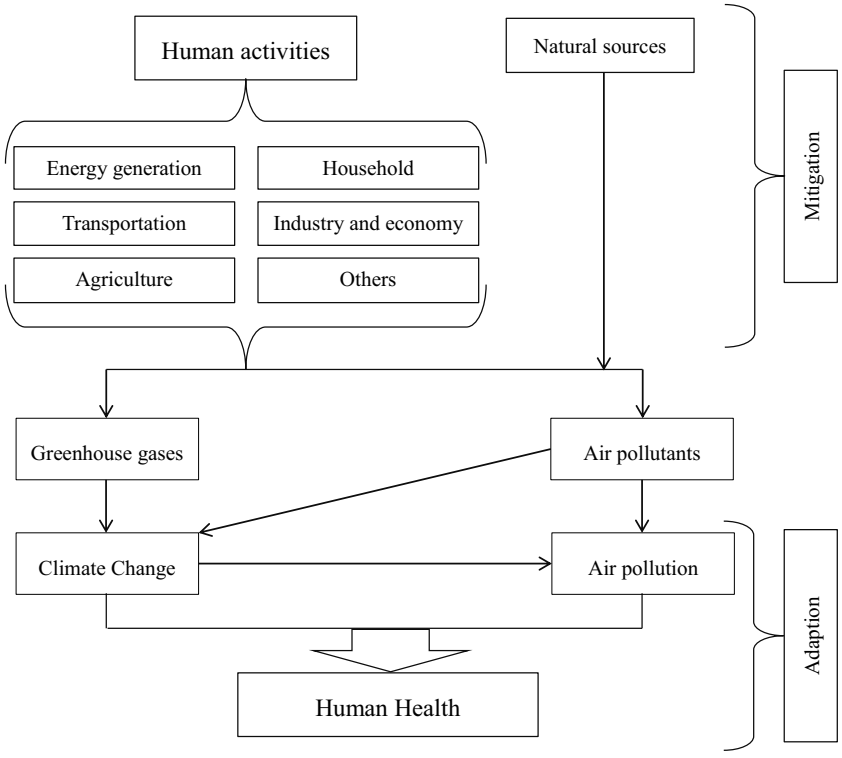

Fig. 2. Potential pathways that greenhouse gas mitigation measures result in health co-benefits.

2.6. Quality assessment

Two authors (JHG and XBL) independently assessed the quality of all included studies. The STROBE approach (Strengthening the Reporting of Observational Studies in Epidemiology) (Vandenbroucke et al., 2007; von Elm et al., 2007) was selected and adapted to describe the reporting quality of the final identified studies. As in previous systematic reviews, the adapted STROBE checklist (Appendix A) was employed to create a binomial scoring system (criterion met = 1, criterion not met = 0) (Aimone et al., 2013; Gao et al., 2014). The score percentage (reporting quality) of each included article was based on the numbers of reporting quality criteria met divided by the total numbers of criteria involved during the quality assessment. Studies that were adjusted for potential confounding factors, quantified health gains of different GHG reduction targets, or monetized health co-benefits of reducing GHG emissions were given higher quality ratings.

2.7. Data synthesis

Because different methods, models, assumptions, GHG reductions policy scenarios, and exposure-response coefficients were applied, cross-study aggregate estimates (meta-analysis) could not be performed. Instead, data synthesis largely consisted of reporting key findings from individual studies and narrative summaries were provided.

Table 1
Search strategy and protocol.

Step 1: Keyword Searches
① "greenhouse gas" OR "GHG" OR "carbon" OR "CO_2" OR "black carbon" OR "methane" OR "ozone"
② "capture" OR "cut" OR "low" OR "limit" OR "mitigation" OR "reduce" OR "sequestration"
③ "benefit" OR "co-benefit" OR "effect" OR "impact" OR "cost" OR "disease burden" OR "health"
In the Title/Abstract for all fields: "①" AND "②" AND "③"
Step 2: "Original and Empirical Study" Filter
Does the primary-sourced study focus on the two aspects that involving both of greenhouse gas emissions reduction and the corresponding public health co-benefits?
Step 3: "Quantitative analysis" Filter
Does the study evaluate or analyze the associations between greenhouse gas emissions reduction and public health co-benefits quantitatively?

3. Results

A total of 10,319 records were identified from the databases and websites, and 94 additional articles were retrieved through references, expert advice, and email alerts (uptodate notifications). After removing duplicates, the titles and abstracts were scanned for relevance. Based on the inclusion criteria, studies that did not involve quantitative association between GHG emissions reduction and health co-benefits were excluded. Then, 205 articles were screened for a full text examination and 36 peer-reviewed articles were retained (Fig. 3).

The identified articles are described in Table 2. In general, the 36 retained studies involved ten developed countries, seven developing countries, and seven global level regions. The association between GHG reductions and health co-benefits was investigated almost entirely by modeling studies, located in one or more of the following sectors: energy generation, transportation, agriculture and food, households, and industrial and economic processes. Seven of the retrieved articles reported the health co-benefits of comprehensive mitigation strategies involving multiple sectors. According to the adapted STROBE checklist, the reporting quality scores for the articles ranged from 57.69% to 86.21%, with 80.56% of the records (27/36) having scores above 70%, indicating relatively high reporting quality.

3.1. Energy generation sector

The health co-benefits of GHG mitigation measures in energy generation, such as low carbon energy production, better energy efficiency, and re-balancing the structure of energy use, were evaluated in several studies. In China, a study by Aunan et al. examined the co-benefits of six abatement measures to reduce emissions (CO_2, PM_{10} and SO_2) related to the use of coal. The authors concluded that increased energy efficiency and the use of "clean coal" technologies are win–win options from a social perspective, and include co-benefits (avoiding losses of 75,000–7,723,000 life years) (Aunan et al., 2004). If GHG reduction targets are set 15% below business-as-usual (BAU) emissions in 2020, Wang and Smith project health benefits from energy efficiency improvements and fuel substitution in China for residential and power generation sectors. They estimated a 4% reduction in the projected mortality, relative to the BAU (Wang and Smith, 1999). A similar study from China found that compared with the BAU, low-carbon energy measures (e.g. improving energy efficiency, expanding natural gas use, and wind electricity generation) could prevent 9870–23,100 deaths in 2020 due to the corresponding reductions in ambient PM_{10} (particulate matter [PM] with an average aerodynamic diameter of 10 μm or less) (Chen et al., 2007). He et al. modeled the benefits of an aggressive energy policy scenario that enhanced air pollution control along with improved energy efficiency and structure and projected that compared with the BAU, by 2030, 1469 million fewer metric tonnes (MT) of CO_2 would be emitted and 135,811 deaths from all causes would be avoided as a result of 12–32% decline in air pollutant concentrations (He et al., 2010). Rive and Aunan conducted another study in China to investigate the benefits of energy-related Clean Development Mechanism (CDM) projects that installed renewable energy, upgraded technologies, and promoted fuels switching, and reported that the CDM projects had simultaneous win-win-win effects on air quality, public health and agriculture (Rive and Aunan, 2010).

Cifuentes et al. investigated the cumulative health impacts of reducing GHG emissions by adopting energy efficiency and fuel substitution measures in four cities: México City, São Paulo, Santiago, and New York from 2000 to 2020 (Cifuentes et al., 2001a). The authors concluded that with respect to BAU in 2020, adoption of these measures could reduce GHG emissions by approximately 13% and prevent about 64,000 (95% confidence interval [CI]: 18,000–116,000) premature deaths as a result of a 10% reduction in exposure to PM_{10} and O_3 associated with GHG mitigation. On a global level, Markandya and colleagues estimated the health benefits of various strategies, such as alternative technologies and fuels, greater use of nuclear power and renewable energy, and carbon capture and storage technology associated with coal burning. They reported that with a 50% reduction target by 2030, compared with BAU, the health gains of full trade scenario in the European Union, China, and India would be approximately 100, 500, and 1500 life-years per million people, respectively. The economic value of the health co-benefits would offset the costs of GHG mitigation, especially in India where levels of pollution is high and mitigation costs are relatively low (Markandya et al., 2009). In another assessment, based on the Representative Concentration Pathway 4.5 (RCP 4.5) scenario, it was estimated that decreasing fossil fuel use and energy demand while increasing forest cover, biofuels use, and carbon capture and geologic storage, could restrict global mean temperature increase to about 2.3 and avoid 2.2 ± 0.8 million premature deaths associated with corresponding reductions in $PM_{2.5}$ and O_3 (West et al., 2013).

3.2. Transportation sector

Less motor vehicle use, and a proportional increase in higher-combustion efficiency and lower-emission vehicles might reduce GHG emissions and avoid premature deaths due to traffic-related air pollution. One study from Thailand investigated the benefits of a GHG

reduction policy scenario that ramped up PM-oriented vehicle inspection and maintenance programs aimed at taking high-emitting vehicles off the road, targeting in particular diesel-fueled vehicles and motorcycles in the Bangkok area. Relative to the BAU scenario in 2015, it was estimated that the program could reduce GHG emissions by approximately 0.4 MT of CO_2 per person yearly, and prevent about 913 premature deaths due to a 25% reduction in roadside PM. The authors estimated that the positive economic impacts would outweigh the cost of policy implementation (Li and Crawford-Brown, 2011). When Woodcock and colleagues chose two settings – London, UK, and Delhi, India – to estimate the health effects of urban land transport by comparing alternative transport scenarios with BAU 2030 projections, they found that reductions in CO_2 emissions through the combination of active travel and lower-emission motor vehicles had the largest benefits (7439 disability-adjusted life years [DALYs] in London and 12,995 in Delhi), greater than those obtained by an increase in active travel or use of lower-emission motor vehicles only (Woodcock et al., 2009). The authors further argued that in order to reduce GHGs and simultaneously improve public health, transport policies should prioritize the needs of pedestrians and cyclists over those of motorists, and increase the acceptability, appeal, and safety of active urban travel. Similar health co-benefits of mitigation measure in transportation sector were also concluded in Basel, Switzerland and Kuala Lumpur, Malaysia, based on modeling investigations (Kwan et al., 2017; Perez et al., 2015).

Several studies have attempted to quantify the benefits of substituting motor vehicle travel with active travel (e.g. walking and cycling). In New Zealand, Lindsay and colleagues reported that despite an additional five cyclist fatalities from road crashes, shifting 5% of vehicle kilometers to cycling would decrease transport-related GHG emissions by 0.4%, and prevent about 122 premature deaths annually as a result of increased physical activity and reduced local air pollution. An important finding in this paper is that the health benefits of moving from motor vehicles to bicycles largely accrue from increasing physical activity, and these outweigh by a large margin the losses resulting from road crash injury (Lindsay et al., 2011). Rojas-Rueda et al. conducted a study in Barcelona, Spain to assess the health impacts of travel by bicycle in an urban environment. Compared with travel by car, an estimated 9062 MT of CO_2 emissions were reduced and 12 premature deaths avoided each year by the shift to cycling (Rojas-Rueda et al., 2011). Maizlish and colleagues quantified the health benefits of transportation strategies to reduce GHG emissions in the San Francisco Bay Area. Although increasing median daily walking and cycling from 4 to 22 min could increase the traffic injury burden by 39% (5907 DALYs), Maizlish et al. found the burden of cardiovascular disease and diabetes would decline by 14% (32,466 DALYs) and the GHG emissions would decrease by 14%. The authors concluded that increased physical activity associated with active transport could generate significant net improvements in public health (Maizlish et al., 2013). A study from Adelaide, South Australia modeled the effects of shifting vehicle kilometers of passenger vehicles to alternative transport (e.g. bicycle and public transport) on air quality, GHG emissions and public health, compared with the BAU 2030 scenario. It concluded that road traffic-related CO_2 emissions would decline by 191,313–954,503 MT annually and that 160–542 premature deaths and 2113–7674 DALYs could be prevented per year due to improved air quality, increased physical activity, and avoided traffic injuries (Xia et al., 2015). David Rojas-Rueda et al. estimated the health impact of increased cycling and increased walking in Six European cities, the authors reported that the two scenarios produced health

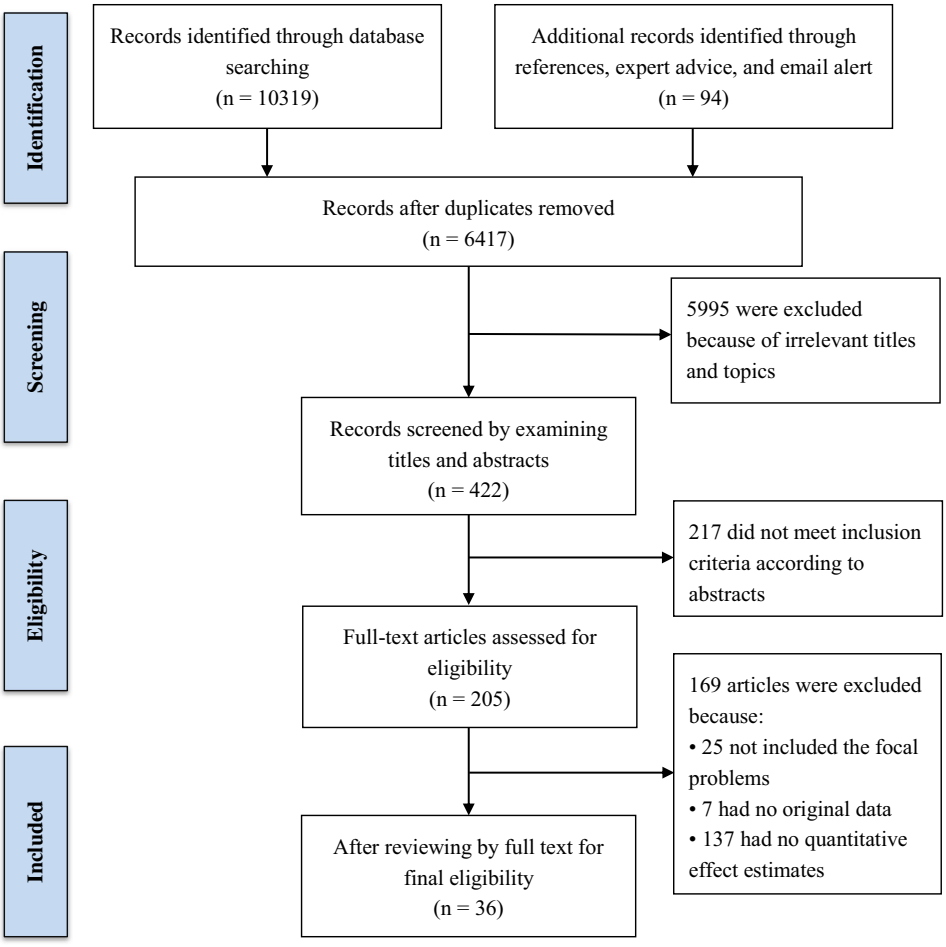
Identification
Screening
Eligibility
Included
Records identified through database searching (n = 10319)
Additional records identified through references, expert advice, and email alert (n = 94)
Records after duplicates removed (n = 6417)
5995 were excluded because of irrelevant titles and topics
Records screened by examining titles and abstracts (n = 422)
217 did not meet inclusion criteria according to abstracts
Full-text articles assessed for eligibility (n = 205)
169 articles were excluded because:
• 25 not included the focal problems
• 7 had no original data
• 137 had no quantitative effect estimates
After reviewing by full text for final eligibility (n = 36)

Fig. 3. Flow chart of screening process of the literature search.

Table 2
Summary of the identified studies on public health co-benefits of greenhouse gas mitigation ($n = 36$).

Author (date)	Study region	Involving sector (s)	Mitigation measures	Benefits for climate	Health co-benefits	Quality (%)
Energy generation and provision sector						
Wang and Smith (1999)	China	Energy in power, household sectors	Energy efficiency and fuel substitution	GHGs reduction is 15% below BAU scenario by 2020	A 4% reduction in the projected mortality of 14 million in China by 2020	70.37
Cifuentes et al. (2001a)	México, Chile, Brazil, and USA	Transportation and energy sectors	Reducing combustion and carbon intensity of fossil fuels	Lower GHG emissions in 2020 by 13% with respect to the BAU case	Avoiding 64,000 (95% CI: 18,000–116,000) premature deaths associated with a 10% reduction in PM and O_3 that because of GHG mitigation, and other health benefits	65.38
Aunan et al. (2004)	Shanxi, China	Industry, power, and rural households sectors	Six different abatement options that could reduce the emissions (CO_2, PM_{10} and SO_2) related to use of coal	The six abatement measures have CO_2 emission-reduction potential from 0.3 to 12.8 million tonnes respectively, and also reduce PM_{10} and SO_2 emissions	75,000–7,723,000 life years lost can be avoided from reduced emission of PM due to the six options for a time period of 90 years	82.14
Chen et al. (2007)	Shanghai, China	Energy, industry, economy, and residential sectors	Energy efficiency improvement, expanding natural gas use, and wind electricity generation	Energy efficiency improve 2% annually from 2000 to 2020, and various other low-carbon measures in natural gas use and wind electricity generation	Compared with the base case scenario, implementation of various low-carbon measures could prevent 9870–23,100 premature deaths because of PM_{10} reduction	73.08
Markandya et al. (2009)	EU, China, and India	Electricity generation	Shift technologies and fuels, decrease the use of coal, use carbon capture and storage, increase nuclear energy and the share of renewable energy	The total CO_2 emissions in 2030 is consistent with the 2050 reduction targets (50% reduction compared with emissions in 1990)	Compared with BAU, the health gains of full trade scenario in EU, China and India would be about 100, 500 and 1500 life-years per million people in 2030, respectively	85.19
He et al. (2010)	China	Energy involving industry, buildings, transportation, and household	Switch energy structure, improve energy efficiency, and control energy consumption	Emissions of CO_2 would reduce 1469 million metric tonnes (MT) compared with the 2030 projected BAU scenario	By 2030, 135,811 all causes mortality would be avoided compared with BAU scenario, and >100 billion US$ of health benefit can be achieved	65.38
Rive and Aunan (2010)	China	Energy	The Clean Development Mechanism (CDM) activities in China to 2012	Annual abatement from CDM projects is forecasted at 319 MT CO_2-eq/yr in 2010, rising to 560 MT CO_2-eq/yr in 2012	Monetized health benefit (avoided deaths) from PM reduction associated with CDM activities is 5359 million RMB (in 2005 terms) per year in 2010	71.43
West et al. (2013)	Global	Energy, economy, and forestry	Decrease fossil fuel use, increase nuclear and renewable energy, increase forest cover and biofuels, grow carbon capture and geologic storage	For RCP4.5, by 2100, CO_2 concentration would decrease from 760 ppm to 525 ppm, and the global mean temperature change is 2.3 relative to the pre-industrial	For RCP4.5, relative to a reference scenario, global GHG mitigation avoids 0.5 ± 0.2, 1.3 ± 0.5, and 2.2 ± 0.8 million premature deaths in 2030, 2050, and 2100	82.14
Transport system						
Woodcock et al. (2009)	London, UK, Delhi, India	Transportation	Use lower-carbon-emission motor vehicles (more efficient engines and fuel switching), and increase active transport	For UK, 60% reduction in transport CO_2 emissions from 1990 levels; while for India (focus on preventing the rise in emissions), 199% increase in CO_2 emissions from 1990	Compared with 2030 projected business-as-usual scenario, the combined mitigation strategy would give the largest benefits (7439 DALYs in London, 12,995 in Delhi, per million population in 1 year)	85.71
Li and Crawford-Brown (2011)	Bangkok, Thailand	Transportation	Enforcing enhanced vehicle inspection and maintenance (I/M) programs targeting diesel-fueled vehicles and motorcycles	The I/M program can produce a GHG emissions reduction of approximately 0.4 MT CO_2 per person per year	913 deaths could be avoided in 2015 associated with 25% PM emission reductions due to I/M programs when compare with the BAU scenario	77.78
Lindsay et al. (2011)	New Zealand	Transportation	Shifting short urban vehicle kilometers (5%) to cycling annually	Reduce transport-related greenhouse emissions by 0.4% each year due to reduced travel kilometers and fuel consumption	Saving 122 deaths annually as a result of increased physical activity and reduced local air pollution from vehicle emissions	74.07
Rojas-Rueda et al. (2011)	Barcelona, Spain	Transportation	Public bicycle sharing initiative, Bicing, promote the bicycle as a common means of transport	As a result of journeys by Bicing, annual CO_2 emissions were reduced by an estimated 9062 MT	As a result of physical activity associated with journeys by bicycle, compared with car users, 12.28 deaths were avoided annually	83.33
Maizlish et al. (2013)	California, America	Transportation	Increasing median daily walking and bicycling from 4 to 22 min (active transport)	Compared with the BAU, the GHG emissions would decrease by 14%	The corresponding burden of cardiovascular disease and diabetes could be reduced by 14% (32,466 DALYs) relative to the BAU	72.00
Perez et al. (2015)	Basel, Switzerland	Transportation	A 10% reduction of traffic on inner roads, and 50% of the private car fleet are based on electric vehicles	20% reduction in CO_2 emissions compared to reference scenario	Prevent 4 DALYs per 1000 population compared to reference 2010 scenario	82.14
Xia et al. (2015)	Adelaide, Australia	Transportation	Changing people's travel behavior toward alternative transport (increase cycling, public and active transport)	The annual reduction of road traffic-related CO_2 emissions would range from 191,313 to 954,503 MT per year depending on the scenarios	Compare with 2030 BAU, 160–542 deaths and 2113–7674 DALYs could be prevented due to improved air quality, improved physical activity and avoided traffic injury	82.14
Rojas-Rueda et al.	Six	Transportation	Increases in bicycle and	The two scenarios would also reduce	The two scenarios produced health	75.00

Table 2 (*continued*)

Author (date)	Study region	Involving sector (s)	Mitigation measures	Benefits for climate	Health co-benefits	Quality (%)
(2016)	European cities		walking trips to 35% and 50% of all trips of each city, respectively	CO_2 emissions in the six cities by 1139 to 26,423 metric tonnes per year	benefits in the six cities, with various extents	
Kwan et al. (2017)	Malaysia	Transportation	Travel modal shift from the private motor vehicles to the use of two upcoming mass rapid transit lines in Greater Kuala Lumpur	Reducing 337,800 t of CO_2-eq per year from private transportation, despite the fact that the use of motor vehicle in the station access-egress would offset 28% of the total savings	Preventing, per year, 5 deaths and 104 DALYs due to the reduced $PM_{2.5}$ concentration, 88 deaths and 6300 DALYs due to the decreased traffic injuries, and 90 deaths and 3200 DALYs because of the increased physical activity	83.33
Agriculture and food sector						
Friel et al. (2009)	UK, and Brazil	Agriculture and food sector	For UK, technological changes reduced emissions in agricultural sector, and an additional 30% reduction in livestock production, and the same reduction proportion of livestock production for Brazil	Attain a 50% reduction in greenhouse-gas emissions from the concentrations recorded in 1990 by 2030	Disease burden decrease by about 15% in UK and 16% in São Paulo city associated with 30% reduction in consumption of saturated fat and cholesterol from animal sources, which caused by the mitigation measures from agricultureand food sector	82.76
Scarborough et al. (2012)	UK	Agriculture and food sector	For scenario 1: 50% reduction in meat and dairy replaced by fruit, vegetables and cereals	19% reduction in agriculture GHG emissions compared with 2008 baseline scenario	36,910 (30,192–43,592) deaths delayed or averted per year compared with 2008 baseline, other scenarios have similar health benefits	69.23
Biesbroek et al. (2014)	Dutch	Food, land use	Substituting one-third (35 g) of the usual daily meat intake with vegetables, fruit-nuts-seeds, pasta-rice-couscous, or fish	The modeled meat-substitution scenario could reduce 4–11% GHG emissions, and 10–12% land use	In the modeled meat-substitution scenario, 6–19% survival rates were increased compared with the reference baseline	84.38
Milner et al. (2015)	UK	Agriculture and food sector	The average UK dietary intake were optimised to comply with the WHO recommendations	An incidental reduction of 17% in GHG emissions	Saving almost 7 million years of life lost prematurely over the next 30 years and increase average life expectancy by over 8 months	82.76
Springmann et al. (2016)	Global	Agriculture and food sector	Transitioning toward more plant-based diets that are in line with standard dietary guidelines	Reduce global food-related GHG emissions by 29–70% compared with a reference scenario in 2050	Reduce global mortality by 6–10% compared with a reference scenario in 2050	86.67
Farchi et al. (2017)	Italy	Agriculture and food sector	Reductions in beef consumption toward patterns more compliant with Mediterranean food pyramid targets (from the current 406 to 150 g/week/person)	According to the Mediterranean food pyramid scenario, CO_2-eq missions could be saved in the range 8000 ± 14,000 Gg per year	The deaths avoidable according to the reduction scenarios for beef consumption were between 2.3% and 4.5% for colorectal cancer, and 2.1–4.0% for cardiovascular disease	71.43
Residential and household sector						
Wilkinson et al. (2009)	UK, and India	Household energy	Strategy of combined fabric, ventilation, fuel switching, and behavioral changes in UK housing stock, and introduce 150 million low-emission household cook stoves in India	Saving 0.6 MT of CO_2 in UK, and 0.1–0.2 MT CO_2-equivalent in India, per million population in 1 year compare with the baseline scenario	The combined strategy in UK and cook stove program in India could avoid 850 and 12,500 DALYs respectively, per million population in 1 year with respect to the 2010 baseline scenario	86.21
Venkataraman et al. (2010)	India	Household sector	Develop cleaner biomass cook stoves and deploy them to all households that currently use traditional cook stoves	80 MT CO_2-eq per year or over 4% of India's total estimated GHG emissions could be avoided if such an initiative were in place today	About 570,000 premature deaths in poor women and children could be avoided	57.69
Industrial and economic process						
Dudek et al. (2003)	Russia	Industry, economy, energy, and forestry sectors	Technological modernization, market liberalization, and energy efficiency improvement	Giving Russia a GHG emission allowances surplus of >3 billion MT of CO_2	Saving about 35,000 lives each year because of the decrease of PM10 and SO_2 resulted from GHGs emissions reduction	62.96
West et al. (2006)	Global	Energy operations, landfills, and wastewater treatment	Using identified global CH_4 abatement options compiled in five industrial sectors	Reducing current global anthropogenic methane emissions by 20% (65 MT/yr) beginning in 2010 and sustained until 2030	Preventing ≈370,000 premature mortalities globally between 2010 and 2030 due to the ozone reduction associated with methane mitigation options	78.57
Anenberg et al. (2011)	Eight major world regions	Three major economic sectors	No presented	Anthropogenic BC emissions are halved globally and individually in eight major world regions and three major economic sectors	157,000 (95% CI: 120,000–194,000) premature deaths could be avoided annually worldwide because of $PM_{2.5}$ reduction associated with the halved BC emissions	72.41
Crawford-Brown et al. (2012)	Mexico	Economic activity, and energy	Climate change policies from the Nationally Appropriate Mitigation Actions of Mexico	For the decarbonisation scenario in 2050, Mexico alone reduces CO_2 emissions by 77%	Compare with the BAU case, 2718 premature deaths per year could be avoided due to reduced ozone and PM under the GHG policy	61.54
Others						
Chae and Park (2011)	Seoul, Korea	Various sectors: household, energy, waste	Integrated Environmental Strategies (IES) (e.g. fuel control and switching, use low emission vehicles, etc.)	Reduce CO_2 emissions of 2014 BAU levels by 10% accompanied with air pollutant reduction	5695 (95% confidence interval 2867–8377) premature deaths were saved as a total of the Seoul	70.37

(*continued on next page*)

		treatment, transportation, industry		(7326 kt of CO_2 emissions reduction)	Metropolitan Area based on the PM_{10} reduction associated with IES	
Anenberg et al. (2012)	Global	Various sectors (e.g. energy, household, food, transportation, etc.)	14 specific methane and black carbon (BC) emission mitigation measures	The measures for cook stoves could achieve a 25% decrease in BC and 80–90% decreases in other species (CO, organic matter, methane, etc.)	Relative to the 2030 reference scenario, 0.6–4.4 and 0.04–0.52 million annual premature deaths could be avoided globally because of reduced concentrations of $PM_{2.5}$ and ozone	81.48
West et al. (2012)	Global	Various sectors: agricultural, industrial and energy sectors	Deploys currently-available methane reduction technologies, and technological innovation	For the three scenarios (A, B, and C), the range of methane emission reductions is 75–180 MT per year in 2030 relative to the base scenario	For the three scenarios, 19,500, 37,800 and 57,200 premature mortalities could be avoided respectively, which associated with ozone reductions due to methane mitigation measures	68.00
Shindell et al. (2012)	Global	Agriculture, food, energy, household, transportation, etc.	14 identified measures targeting methane and BC emissions reductions	Reduce projected global mean warming ~0.5 by 2050 in comparison with the reference base	The strategy avoids 0.7 to 4.7 million annual premature deaths due to ozone reductions associated with mitigation measures in 2030	84.62
Rafaj et al. (2013)	Global, and key world regions (EU, China, India, and the United States)	Energy, household, transportation, industry, and agriculture, etc.	Various mitigation measures involving industrial processes and energy activities for reducing the emissions of air pollutants and GHGs	For mitigation scenario, global mean temperature does not increase beyond 2 °C, and global CO_2 emissions reduced by 80% in 2050 compared to the baseline emission level	By 2050, for China in the Mitigation scenario, loss in statistical life expectancy due to $PM_{2.5}$ is halved, and premature deaths attributable to ozone are reduced annually by 20,000 cases when compared with the Baseline, similar results also be observed in other key regions	73.08
Jensen et al. (2013)	UK	Agriculture and food, transportation household energy	Cleaner vehicles and increase active travel, reduce livestock production, improve energy efficiency of household, etc.	In 2030, the emission reduction of household, transport, and agriculture sectors would be 50%, 60%, 50% in different scale of UK, respectively	For the three kinds of mitigation strategies, the macro effects of health co-benefits produced from the health-related shocks are ranged from 448 to 18,854 (£ million)	76.92
Sabel et al. (2016)	Five European and two Chinese cities	Urban transport, building fabric and energy supply	Heat, powerplant fuel peat and oil changed to wood; biofuels for transport; 10% reduction in private car use and 50% growth in electric cars; building renovation, etc.	By 2020, all policies modeled reduced CO_2 emissions relative to the BAU, with different extents	With the exception of using biomass for domestic heating, the GHG reduction policies were likely to improve health, especially in areas few such policies have been adopted before, although the benefits tended to be slight	77.78

Abbreviations: BAU, business as usual; BC, black carbon; CDM, Clean Development Mechanism; DALYs, disability-adjusted life-years; EU, European Union; GHGs, greenhouse gas; MT, metric tonnes; PM, particulate matter; PM_{10}, particulate matter with an average aerodynamic diameter of 10 mm or less; $PM_{2.5}$, particulate matter with aerodynamic diameter 2.5 μm or less; RCP, Representative Concentration Pathway scenario; SO_2, sulfur dioxide.

benefits in all cities, while reduced CO_2 emissions in the six cities by 1139 to 26,423 MT per year (Rojas-Rueda et al., 2016).

3.3. Agriculture and food sector

The potential contributions of decreases in the consumption of food from animal sources (while meeting nutritional requirements) and improvements in agricultural technologies to the targets of GHG emissions reduction and public health have been investigated in different areas. Friel et al. conducted a study to estimate the co-benefits of mitigation strategies for the agricultural sector in the UK and São Paulo, Brazil. The authors concluded that a combination of agricultural technological improvements and a 30% reduction in livestock production could achieve a 50% GHG emissions reduction target by 2030 relative to the concentrations in 1990, and trim the burden of nutrition-related disease by approximately 15% in the UK and 16% in São Paulo (Friel et al., 2009). The authors also called on coordinated intersectoral actions worldwide in order to address potential challenges and provide affordable, healthy, and climate-friendly diets for all societies. Another study from the UK that modeled the health impacts of sustainable dietary scenarios estimated that a reduction in consumption of meat and dairy products replaced by fruit, vegetables and cereals or other low-emission foods would lead to a 3–19 reduction in GHG emissions, while delaying or averting 1999–36,910 premature deaths annually (Scarborough et al., 2012). Biesbroek et al. suggested that compared with the BAU, the modeled substitution of 35 g/day of usual daily meat intake with vegetables, pasta-rice-couscous, fruit-nuts-seeds, or fish could reduce GHG emissions by 4–11% while increasing survival rates of the targeted population by 6–19% (Biesbroek et al., 2014). Another study from the UK estimated that if the average UK dietary intake were optimised to comply with the WHO recommendations, there were almost 7 million years of life lost over the next 30 years could be saved, and incidentally reduced 17% GHG emissions (Milner et al., 2015). Compared with a reference scenario in 2050, Marco Springmann et al. concluded that transitioning toward more plant-based diets that are in line with standard dietary guidelines could reduce global food-related GHG emissions by 29–70%, while decreased global mortality by 6–10% (Springmann et al., 2016). Similar ancillary health gains from mitigation measure in food consumption were also reported in Italy (Farchi et al., 2017).

3.4. Residential and household sector

Studies have examined environmental and health impacts of GHG mitigation measures, including improvements in the efficiency of household energy and clean household stoves. Wilkinson et al. investigated the health and climate impacts of hypothetical strategies to improve energy efficiency in the UK housing stock and to introduce 150 million low-emission household cook stoves in India (Wilkinson et al., 2009). For housing in the UK, a mitigation strategy of combined building fabric, ventilation, fuel switching and behavioral changes brought about a savings of 0.6 MT of CO_2 and 850 fewer DALYs per million people per year with respect to the 2010 baseline scenario, while the cook stove program in India achieved savings of 0.1–0.2 MT of CO_2-eq and 12,500 fewer DALYs per million people per year. On this basis, household

energy interventions may provide a cost-effective means to achieve both population health and climate mitigation goals (Wilkinson et al., 2009). Another study from India estimated the benefits of initiatives to develop low-emission biomass cook stoves in place of traditional stoves. The authors estimated savings of 80 MT of CO_2-eq per year and approximately 570,000 fewer premature deaths of poor women and children due to improved air quality (Venkataraman et al., 2010).

3.5. Industrial and economic processes

Dudek et al. estimated that market liberalization, market reforms, and technological modernization in Russia provided the country with a GHG emission allowance surplus of more than three billion MT of CO_2, while averting about 35,000 premature deaths per year due to the lower levels of PM_{10} and SO_2 that resulted (Dudek et al., 2003). West et al. investigated the health co-benefits of reducing current global anthropogenic methane emissions from industrial sector by 20% (65 MT/year) beginning in 2010 and sustaining the reductions through 2030. They found that approximately 370,000 premature deaths would be prevented globally due to reductions in surface ozone concentrations. Methane mitigation, the authors concluded, may be a cost-effective instrument to achieve gains for air quality, public health, climate, energy, and agriculture (West et al., 2006). Anenberg et al. explored the consequences of halving anthropogenic BC emissions in eight world regions and three major economic sectors. An abatement policy of this kind could avert 157,000 (95% CI: 120,000–194,000) premature deaths globally per year, it was estimated (Anenberg et al., 2011). Another study from Mexico modeled the health co-benefits of a 77% CO_2 emissions reduction throughout Mexican economy as a result of climate change mitigation policies and concluded that 2718 premature deaths could be avoided per year due to reduced ozone and PM concentrations (Crawford-Brown et al., 2012).

3.6. Other

Other papers reported ancillary health benefits of certain comprehensive climate-motivated strategies that touched multiple sectors (e.g. energy, transportation, industry, household, agriculture, or waste treatment). Chae and Park reported that an Integrated Environmental Strategies (IES) scenario in South Korea (fuel control, energy structure switching and use of low emission vehicles) could reduce CO_2 emissions by 10% compared with the 2014 figure, and avert 5695 (95% CI: 2867–8377) premature deaths associated with PM_{10}. These savings exceeded what would be obtained by individual scenarios involving air quality management or GHG reduction measures (Chae and Park, 2011). A study from the UK performed a health-focused, macroeconomic assessment of three contingent GHG mitigation strategies, namely, urban transport, food and agriculture, and household energy efficiency strategies. The results suggested that these strategies could reduce GHG emissions by 50–60 in the three sectors, respectively, while generally resulting in health co-benefits of varying cost-effectiveness (Jensen et al., 2013). On a global scale, Rafaj and colleagues modeled the impacts of global 2 targeted mitigation policies on climate, air quality and public health. They reported that global CO_2 emissions would need to decrease by 80% by 2050 with respect to the baseline emissions level. In China, losses in life expectancy due to $PM_{2.5}$ would be halved and premature deaths attributable to ground level ozone would be reduced annually by 20,000 (Rafaj et al., 2013).

Anenberg et al. simulated the influence of 14 individual CH_4 and BC emission control measures on climate and outdoor concentrations of $PM_{2.5}$ and O_3, and estimated the health benefits relative to the reference scenario for 2030. The measures could prevent 0.6–4.4 and 0.04–0.52 million premature deaths associated with $PM_{2.5}$ and O_3, respectively, around the globe each year (Anenberg et al., 2012). Similarly, Shindell and colleagues studied the effects of 14 identified measures targeting CH_4 and BC emissions on climate change and public health. Such measures could reduce global warming by approximately 0.5 by 2050, the authors concluded, and might prevent 0.7–4.7 million premature deaths annually due to decreased air pollution (Shindell et al., 2012). West et al. examined the health co-benefits of CH_4 emissions reduction scenarios in energy production, waste treatment, industry and agriculture sectors from a global perspective. Between 19,500 and 57,200 ozone-related premature deaths could be avoided in 2030 depending on the scenarios, this study reported (West et al., 2012). Clive E. Sabel et al. modeled the impact of adopted urban climate change mitigation policy scenarios in transport, buildings and energy sectors, and concluded that by 2020, with different extents, all policies modeled reduced CO_2 emissions, with additional health benefits (Sabel et al., 2016).

4. Discussion

We have summarized what is known about health co-benefits associated with GHG mitigation in energy generation, transportation, agriculture and food, household, and industry sectors at global, national and regional levels. Mostly positive associations between GHG emissions reduction and ancillary health gains were reported in the 36 studies that were retained from the literature search. This was true in both high- and low-income countries, and comprehensive measures tended to provide greater health benefits than single-sector interventions. To the best of our knowledge, this is the first time that current evidence of health co-benefits in relation to GHG reductions from various economic sectors has been comprehensively reviewed and summarized.

We found that GHG mitigation policies in five domains – energy generation, transportation, food and agriculture, household, and industry and economy – are often, although not always, health-promoting. In some cases, the positive health consequences are substantial, cost-effective, and attractive to multiple parties (Haines et al., 2009; Patz et al., 2014; Watts et al., 2017b). The health co-benefits of mitigation measures appear in a number of forms, depending on the sources of GHG emissions being reduced. For instance, reducing GHG emissions in energy generation sector impacts on health through the corresponding reductions of common air pollutants (Fig. 2), such as PM, BC, SO_2, and NOx (Chen et al., 2013; Crawford-Brown et al., 2012; Dudek et al., 2003). In the transportation sector, in addition to the co-control of GHGs and air pollutant emissions and the health gains from improved air quality, GHG mitigation activities such as the shift from vehicular to active travel act through other mechanisms, including increases in physical activity, social contact, and the opportunity to interact with the natural environment. Consequently, co-benefits may include reductions in cardiovascular disease, type 2 diabetes, colon and breast cancer and depression (Creutzig et al., 2015; Rissel, 2009; Woodcock et al., 2009; Xia et al., 2015; Xia et al., 2013). Reducing intake of foods from animal sources in high-consumption populations could reduce GHG emissions and substantially benefit public health, for example, via reductions in type 2 diabetes, ischemic heart disease, and the prevalence of obesity (Friel et al., 2009; Kelly et al., 2017; Macdiarmid, 2013; McMichael et al., 2007). Mitigation actions in the residential and household sector, such as improvements in combustion energy efficiency (Dora et al., 2011), substitution of traditional cooking and space heating practices with clean fuel technology and lower-emission household appliances (Ochieng et al., 2013; Venkataraman et al., 2010; Wilkinson et al., 2009), and saving energy through improvements in fabrics, fuel switching, and behavioral changes (Wilkinson et al., 2009) could bring about health co-benefits in addition to reductions in GHG emissions (Anenberg et al., 2013; Cifuentes et al., 2001b). For industrial and economic processes, air quality improvements and health gains could be achieved through measures that improve energy efficiency and promote the use of clean and renewable energy (Crawford-Brown et al., 2012; He et al., 2010; Ren et al., 2012; Zhai et al., 2011). Comprehensive strategies that involve multiple economic sectors could, in theory, multiply the health/climate co-benefits (Anenberg et al., 2012; Chae and Park, 2011; Shindell et al., 2012; Wilkinson et al., 2009).

An array of tools to estimate the health co-benefits of climate change mitigation are currently available. Two types of risk evidence, epidemiological and toxicological, are routinely used for environmental health assessments (McKinley et al., 2005; Smith and Haigler, 2008). Based primarily on the existing epidemiological evidence, a variety of methods such as comparative risk assessments (Friel et al., 2009; Markandya et al., 2009; Woodcock et al., 2009); complex mechanistic components (Wilkinson et al., 2009); and macroeconomic, technological, and behavioral models (Jensen et al., 2013; Rojas-Rueda et al., 2011; Shindell et al., 2012) were employed to model the co-benefits of GHG mitigation strategies. In general, studies of health co-benefits follow a path in which there are four key steps, including scoping/baseline, impact assessment, valuation procedures, and sensitivity/uncertainty analyses (Fig. 4) (Bell et al., 2008; Patz et al., 2008; Remais et al., 2014; Smith and Haigler, 2008).

Due to variations in study design, mitigation scenarios, exposure-response functions, model assumptions and selection of methods, it is often difficult to compare health co-benefits assessments even if the study area and target time scales are identical (Bell et al., 2008; Haines et al., 2009; Remais et al., 2014). In order to conduct the most robust evaluation of ancillary health benefits, studies have recommended relying on the most defensible and transparent methods, the application of multiple approaches, and extensive sensitivity analyses (Bell et al., 2008; Patz et al., 2008). Effort is now being applied by international agencies such as WHO and researchers in the field to improve the consistency and portability of models, so that assessments can be readily repeated, extended and modified to assist policy-makers (Kelly et al., 2017; Majid Ezzati et al., 2004; Smith and Haigler, 2008; Watts et al., 2015; Watts et al., 2017a). Although uncertainties and ambiguities remain, these methods may represent the best possible compilation and practice of knowledge to date regarding how to carry out fair, balanced, and meaningful evaluations of activities to mitigate climate change and protect human health (Bell et al., 2008; Patz et al., 2008; Smith and Haigler, 2008). Thus, shared international commitments or voluntary engagements in the use of standard methods to estimate the health co-benefits of GHG abatement should be encouraged.

To date, few health co-benefit assessments have been conducted in developing countries, and the gap is particularly noticeable in Africa and the Middle East. Hundreds of millions of people in these areas suffer high levels of environmental pollution and are also struggling with poverty, lack of secure water and sanitation services, malnutrition, and natural disasters (Anenberg et al., 2010; Haines et al., 2009; Patz et al., 2008). The health disparities that exist currently in these regions will be magnified by climate change and ecosystem disruption, meaning the countries or populations most vulnerable to climate change are, ironically, those least responsible for causing the issue (Barros et al., 2014; Chae and Park, 2011; Pachauri et al., 2014b; Smith et al., 2014; West et al., 2012; Whitmee et al., 2015). Those studies that have paid attention to co-benefits of GHG reductions in developing regions generally report the potential for climate and health benefits are considerable (Haines et al., 2009; Shindell et al., 2012; West et al., 2012; West et al., 2013). Potentially, the largest health gains of all can be made in developing regions include but are not limited to the reasons presented in Table 3. The health co-benefits of GHG abatement may contribute to reducing inequality in GHG emissions reduction responsibilities and in the health consequences of climate change between low- and high-income countries (Chae and Park, 2011; Haines et al., 2009; Patz et al., 2008; Quam et al., 2017). Many developing countries wish to simultaneously promote economic growth and at the same time cut pollution, limit GHG emissions, and protect public health concerns. These goals are not necessarily inconsistent with one another, and are profoundly important, because the active participation of developing countries in GHG reduction efforts is essential in curbing global warming (Chae and Park, 2011; Shindell et al., 2012). The present review revealed that comprehensive mitigation strategies involving multiple economic sectors generally provide greater health gains and higher GHG emissions reduction that are both welfare-enhancing and cost-effective (Anenberg et al., 2012; Jensen et al., 2013; Shindell et al., 2012; West et al., 2012; Woodcock et al., 2009). For countries with limited economic resources facing severe air pollution issues, the implementation of integrated measures is crucial to simultaneously reducing air pollutants and GHG emissions in order to maximize health co-benefits (Fig. 2) and to prepare for future agreements on climate change mitigation (Chae and Park, 2011; Pachauri et al., 2014b; Watts et al., 2015).

4.1. Challenges and uncertainties in estimating health co-benefits

Estimating health co-benefits of GHG emissions reduction is, in some ways, alien to conventional epidemiological approaches and assessment studies, presenting several challenges or uncertainties (Table 4) (Bell et al., 2008; Haines et al., 2009; Pachauri et al., 2014b; Patz et al., 2008; Remais et al., 2014; Smith and Haigler, 2008; Watts et al., 2015; Younger et al., 2008). Simply observing long-term trends in GHG abatement-related health outcomes and attributing these changes directly to mitigation measures are insufficient. Health professionals should work closely with those involved in strategic planning and performance appraisals in relevant sectors to ensure that the assumptions and scenarios on which they are based are transparent and founded on the best available evidence (Bell et al., 2008; Haines et al., 2009).

Several important sources of uncertainty arise in relation to the key steps of health co-benefits assessment. Given the nature of the information on which the co-benefits assessments must draw, the limitations in data quality and availability and the debate over exposure–response functions for health outcomes, estimating the total health gains from the decrease in air pollution associated with GHG emissions reductions remains a challenge (Bell et al., 2008; Chae and Park, 2011; Cifuentes et al., 2001a). There is substantial compositional variation worldwide for air pollutant mixtures and some evidence suggests that the toxicity of the mixtures may vary (Smith et al., 2009). The concentrations and components of air pollution mixtures, the specific pollutants responsible for adverse effects, concentration-mortality relationships, population characteristics, health status, population-specific activity patterns and lifestyles, climate and seasonal characteristics, and medical care infrastructure may differ substantially among different regions (Anenberg et al., 2011; Aunan et al., 2004; Gao et al., 2017; Markandya et al., 2009). Transferring risk estimates (e.g. baseline mortality rates, exposure-response functions, or health economic assessment tools) from one population to another is also encumbered with uncertainties (Anenberg et al., 2011; Bae and Park, 2009; Bell et al., 2008; Haines et al., 2009; West et al., 2006).

On the one hand, underestimates may characterize many parts of the assessment process in modeling studies for the following reasons: health effects of only one or a few air pollutants are considered, not all of the common pollutants (Cifuentes et al., 2001a; Markandya et al., 2009; Xia et al., 2015); the true harmful agent is not the pollutant under study, while related pollutants or groups of pollutants with similar sources or formation pathways are included in the evaluation models (Bell et al., 2008); health impacts due to exposure to indoor air pollution, forest fires and dust are often not included (Chen et al., 2007; Pechony and Shindell, 2010; West et al., 2013); in some cases only acute exposure impacts and short-term health co-benefits are estimated (Bell et al., 2008; Kunzli et al., 2001); future population growth and certain subpopulations are neglected during the health co-benefits assessment (Anenberg et al., 2012; West et al., 2013); only the well-known health consequences associated with environmental hazards are evaluated, while the unknown health endpoints or less severe health events are not considered (Anenberg et al., 2011; Haines et al., 2009; Ito et al., 2005); a number of health and economic endpoints are unquantified because of inadequate exposure-response relationships (Bell et al., 2008; Voorhees and Uchiyama, 2007); potential savings in GHG emissions are not included (Friel et al., 2009); and

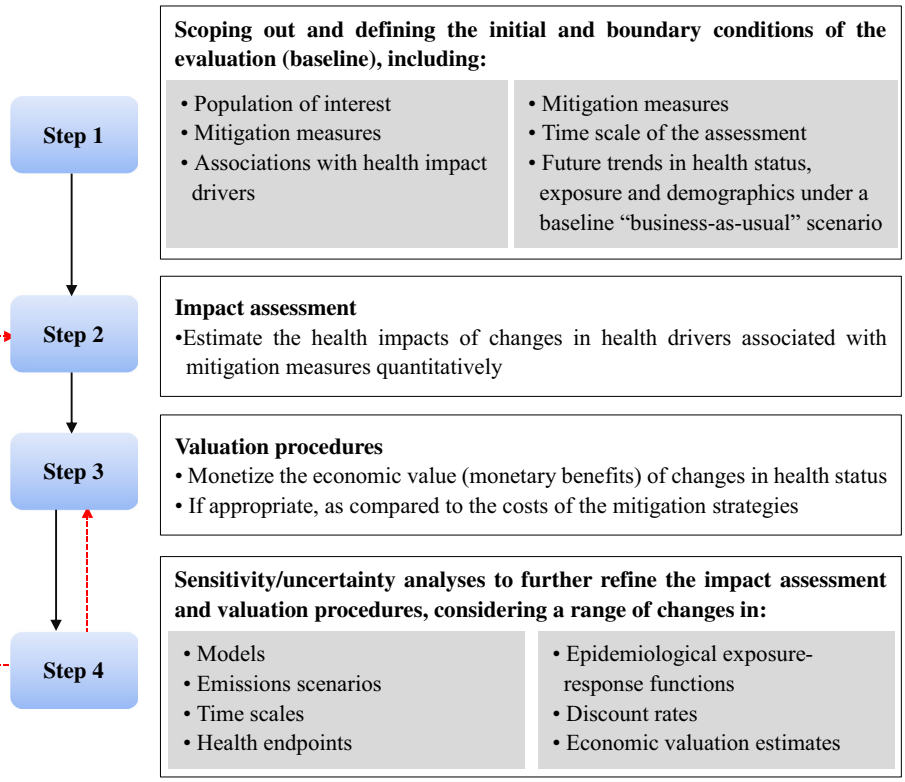
Step 1
Scoping out and defining the initial and boundary conditions of the evaluation (baseline), including:
• Population of interest
• Mitigation measures
• Associations with health impact drivers
• Mitigation measures
• Time scale of the assessment
• Future trends in health status, exposure and demographics under a baseline "business-as-usual" scenario
Step 2
Impact assessment
•Estimate the health impacts of changes in health drivers associated with mitigation measures quantitatively
Step 3
Valuation procedures
• Monetize the economic value (monetary benefits) of changes in health status
• If appropriate, as compared to the costs of the mitigation strategies
Step 4
Sensitivity/uncertainty analyses to further refine the impact assessment and valuation procedures, considering a range of changes in:
• Models
• Emissions scenarios
• Time scales
• Health endpoints
• Epidemiological exposure-response functions
• Discount rates
• Economic valuation estimates

Fig. 4. Structure and key steps of approaches commonly used in health co-benefits assessment of GHG mitigation.

indirect health gains due to positive impacts of GHG reductions on ecosystems, water supplies and quality, and agriculture are not included (Cheng and Berry, 2013; Cifuentes et al., 2001a; Shindell et al., 2012; West et al., 2006).

On the other hand, some assumptions in assessment models may lead to overestimation of the health co-benefits of GHG mitigation strategies for the following reasons. First, the estimated health benefits may be based on assumptions for an immediate and/or maximum level of national participation and full implementation of each future mitigation strategy and reduction scenario. In reality, there are political, practical and institutional barriers when implementing policy options and related effects on public health will only become evident over time (Chae and Park, 2011; Friel et al., 2009; Haines et al., 2009). Second, the magnitude of the health effects might be modified in subsequent years because of changes in population structure, baseline mortality rates, background frequency of specific diseases, and social health-care interventions (Chae and Park, 2011; Collaborators, 2015; Curioni et al., 2009). Third, reduction scenarios developed to conduct health co-benefits assessments are not consistent with the actual decreases in pollutant emissions, especially for societies undergoing rapid development (Haines et al., 2009; Klimont et al., 2013; Smith et al., 2009; West et al., 2013). Finally, in food and agriculture sector, assumptions are made that reductions in the production of livestock will directly result in commensurate reductions in population's intake of saturated fat and cholesterol from animal sources (Friel et al., 2009).

In terms of the challenges and uncertainties associated with many parts of the health co-benefits assessment process in modeling studies, additional consideration and research is needed to reduce relevant underestimation or overestimation and to clarify the overall potential of GHG mitigation strategies that improve (or in some cases, negatively impact) public health. For instance, although epidemiological-based studies on numerous regions have advantages over single-city studies as they are less subject to sample size concerns, choices regarding exposure–response functions, health effect thresholds, or health economic assessment tools should be based on selecting a city or region that matches or is similar to that of the health co-benefits assessment or these studies should develop and apply city-specific parameters and indices to minimize related uncertainties (Bell et al., 2008; Chae and Park, 2011; Dominici, 2002; Remais et al., 2014; Swanson et al., 2014). It is necessary to create a set of assumptions to develop models that quantify the health co-benefits of GHG emissions reduction. Different assumptions may significantly impact the inputs, lead to substantial variations in outputs and estimates of the assessment models (Haines et al., 2009; Xia et al., 2015; Zhang et al., 2016). Thus, a series of sensitivity analyses exploring alternative assumptions regarding future trends and relations between relevant policy scenarios and health outcomes are needed in order to assess the uncertainties and applicability of key parameters and the impacts of related assumptions on the co-benefits assessments (Bell et al., 2008; Haines et al., 2009; Remais et al., 2014).

Table 3
Potential reasons for the larger health gains of GHG mitigation can be made in developing regions.

Items	Reasons	References
1	• Rely mainly on the inefficient combustion of biomass fuels for household energy	(Venkataraman et al., 2010; Wilkinson et al., 2009)
2	• Highly populated regions of the world	(Shindell et al., 2012)
3	• Populations are typically exposed to higher concentrations of air pollutants	(Anenberg et al., 2011; West et al., 2013)
4	• Have the highest baseline mortality rates	(West et al., 2012)
5	• Air quality policies and regulations to limit pollutants emissions are lacking or unenforced	(Patz et al., 2014; Rafaj et al., 2013)
6	• Populations are vulnerable because of poor nutrition, health infrastructure and access to health care	(Haines et al., 2009; Watts et al., 2015; Whitmee et al., 2015)

Table 4
Challenges and uncertainties in the health co-benefits assessment of GHG emissions reduction.

Number	Challenges/Uncertainties
1	The development of credible scenarios for GHG emissions under "business-as-usual" and mitigation projections over relevant time course
2	The energy structure, transportation patterns, land use, building construction, technology innovation, levels of exposure to health drivers, and demographic characteristics may change substantially along with time, which have major implications for public health
3	Different population subgroups (age, gender, racial or socio-economic groups) may face disproportionate health impacts from air pollution or other environmental hazards
4	There are large number of health outcomes potentially affected by GHG reductions
5	There are short- to medium-term as well as the long-term health benefits associated with GHG mitigation actions
6	The varying lag times between changes in exposure and changes in health outcomes
7	Different economic valuations of health outcomes between developed and non-industrialized countries
8	Controversial aspects of key parameters such as discount rates and the terms involved in the exposure-response functions

4.2. Strengths and limitations

The present study has some noteworthy strengths. Firstly, it is the first comprehensive review conducted specifically to assess the quantitative relationship between GHG emissions reduction and health co-benefits in different economic sectors. The health co-benefits associated with GHG mitigation measures can provide policy makers with additional incentives, raising their willingness to go beyond curtailing climate change and to reduce the emissions of both GHGs and air pollutants (Bollen et al., 2009; Crawford-Brown et al., 2012; Patz et al., 2014; Watts et al., 2017b). Secondly, we summarized evidence relating to the health co-benefits of GHG abatement measures in five economic sectors. The findings provide a more complete understanding of the multiple effects of GHG mitigation strategies, improve the ability to marshal additional political support, and inform decision-making (Cheng and Berry, 2013; Crawford-Brown et al., 2012; Kelly et al., 2017). Thirdly, the potential mechanisms and pathways through which GHG reductions bring health co-benefits were discussed. This information may provide insight into the obstacles that might be encountered in implementing GHG mitigation policies and how they can be overcome (Crawford-Brown et al., 2012; Nemet et al., 2010; Nocera et al., 2015). Lastly, current challenges and uncertainties associated with the health co-benefits assessments of GHG reductions were explored. The discussion may offer substantial information with regard to the pros and cons of different approaches used to estimate the health benefits. Despite the wide range of uncertainties characterizing many parts of the process of modeling studies, appealing health co-benefits resulting from GHG mitigation strategies can be anticipated (Aunan et al., 2004; Cifuentes et al., 2001a; Haines et al., 2009; Matus et al., 2008; Quam et al., 2017).

Several limitations of this review must be acknowledged. First, only studies published in English were included in the present review. Thus, information of studies in other languages could not be captured. Second, this study may be limited due to its emphasis on original, peer-reviewed journal articles and potentially useful evidence in other studies on the topic of health co-benefits of GHG mitigation may have been missed. For example, relevant reports or books from UN-related organizations (e.g. WHO, UNFCC, and IPCC) and other non-governmental organizations were excluded. However, we cited and presented this information extensively in our discussion. Third, despite the fact that a comprehensive literature search was conducted, it is unlikely that all of the relevant studies were identified and publication bias cannot be completely eliminated.

5. Conclusion

In the present paper, the available evidence of the quantitative associations between GHG emissions reduction and public health co-benefits were identified and summarized. The results generally suggested that GHG mitigation strategies in energy generation, transportation, food and agriculture, household, and industry could, simultaneously, bring ancillary health benefits, while comprehensive measures across various sectors tend to provide greater health gains. In addition to raising awareness, findings from this review can provide valuable information for central and local governments, non-governmental organizations, policy makers, and other relevant stakeholders concerned with the development and implementation of low carbon technologies and policies. Additionally, the potential health co-benefits and cost savings that offset or even outweigh the costs of implementing abatement measures can improve the acceptability of GHG mitigation strategies. This can help policy makers to identify the most cost-effective mitigation measures in achieving the given reduction objectives and to prioritize the use of resources in the fight against climate change.

In order to avert climate change, international negotiations are in progress regarding further GHG reductions and increasing the number of countries with binding commitments to reduce GHG emissions. During the 2015 UNFCCC COP21 (the 21st session of the Conference of the Parties), for the first time in over 20 years of UN negotiations, universal agreement was achieved on both climate change and mitigation actions. The strategic significance of the health co-benefits of GHG mitigation measures is crucial because policies aimed at reducing GHG emissions often receive weak support in many countries, but may gain support if the health co-benefits are included in cost-effective analyses. This would help bridge the development gap between low- and high-income countries and strengthen the rationale for converging GHG mitigation schedules. Thus, it appears likely that the health co-benefits may not only offset the costs of GHG mitigation policies to some extent, but may also offer a unique opportunity to promote the development and implementation of low carbon policies. In addition, quantitative information on the extent and magnitude of the health co-benefits related to GHG reductions may be of particular interest for policy makers and climate negotiators when faced with difficult choices regarding specific mitigation strategies that are vital components of international, national, or regional actions to protect the population from the dangers of climate change.

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Conflicts of interest

The authors all declare they have no actual or potential competing financial interests.

Authors' contributions

JHG and QYL conceptualized, designed and initiated the study, and drafted the initial manuscript. JHG, JL, SHG and XBL involved in the

literature search, study selection, data extraction, and quality assessment. JHG, SK, SV, PW, AW, HXW, JW, XQS, YKZ, JZ and QYL involved in the development of methodology and discussion of article structure, and reviewed and revised the manuscript. All authors read and approved the final manuscript as submitted.

Appendix A. Supplementary data

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